Comparative Assessment of Structural Floor Systems in Hot-Arid Climates: Cost, Constructability, and Embodied Carbon Implications for Saudi Arabia

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***Abstract*—Early-stage structural system selection is a critical yet often underexplored determinant of project cost, construction efficiency, structural performance, and embodied carbon. In the context of Saudi Arabia, the significance of these decisions is intensified by hot-arid climatic conditions, fast-track delivery requirements, and ambitious national sustainability targets under Vision 2030. This study delivers a rigorous quantitative and qualitative comparison of five structural floor systems widely adopted in the Kingdom—reinforced concrete flat slabs, post-tensioned slabs, waffle slabs, precast hollow core slabs, and steel frames with composite decks—using a standardized 1000 m² floor plate with a 9 m × 9 m column grid to ensure consistency. The analysis integrates preliminary design quantities with internationally recognized embodied carbon datasets and is strengthened by sensitivity analyses addressing span variability and uncertainty in carbon factors. The findings demonstrate that post-tensioned and hollow core systems can reduce embodied carbon by up to 55% compared with conventional flat slabs, while steel composite systems offer clear constructability and schedule advantages at a higher environmental cost. By explicitly linking structural efficiency, constructability, and localized sustainability considerations, this paper provides a robust, decision-oriented framework that supports early-stage system selection for large-scale developments in hot-arid regions.**

***Keywords*—embodied carbon, structural systems, post-tensioned slabs, hollow core slabs, waffle slabs, Steel composite, hot-arid climate, Saudi Arabia, sustainable construction**

I. Introduction

The global construction sector is responsible for approximately 37% of energy-related carbon dioxide emissions, with embodied carbon from construction materials representing a rapidly increasing share as operational energy efficiency improves [1, 2]. Structural materials such as reinforced concrete and steel contribute significantly to these emissions due to cement production, steel manufacturing, and material-intensive structural configurations [3].

In hot-arid regions such as the Middle East, operational energy demand has traditionally dominated sustainability discussions due to cooling requirements. However, recent studies indicate that as building envelopes and mechanical systems become more efficient, embodied carbon can account for up to 50% of a building's total life-cycle emissions, particularly in reinforced concrete structures [4, 5]. Consequently, early-stage structural system selection has emerged as a critical opportunity for carbon reduction without compromising safety or functionality.

Several structural floor systems are commonly adopted in commercial and hospitality developments, including reinforced concrete flat slabs, post-tensioned slabs, waffle slabs, precast hollow core slabs, and steel composite systems. Previous research has demonstrated that post-tensioned systems can achieve material savings of 20–40% compared to conventional reinforced concrete slabs [6, 7], while precast hollow core systems offer further reductions through optimized factory-controlled production [8]. Waffle slabs provide structural efficiency for long spans but introduce constructability and formwork complexity [9]. Steel composite systems enable rapid construction but often exhibit higher embodied carbon due to steel-intensive components [10].

Despite the growing body of international literature, comparative assessments tailored to hot-arid climates and regional construction practices in Saudi Arabia remain limited. Most existing studies rely on European or temperate-climate assumptions, which may not accurately reflect local material sourcing, construction methods, or project constraints. Furthermore, few studies integrate embodied carbon analysis with constructability and functional flexibility considerations, despite their critical importance for decision-making in large-scale developments.

In parallel, Saudi Vision 2030 emphasizes sustainable urban development, carbon reduction, and responsible resource utilization within the construction sector [11]. As

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green building certifications and sustainability metrics become increasingly embedded in public and private developments, there is a growing need for region-specific, quantitative, and decision-oriented frameworks to guide early-stage structural system selection.

Accordingly, this study presents a comparative assessment of five widely used structural floor systems under a standardized Saudi Arabian case study, combining quantitative embodied carbon evaluation with qualitative constructability and functional considerations. By integrating realistic regional assumptions with early design-stage analysis, the study aims to support informed structural decision-making in hot-arid climates and contribute to sustainability-driven development aligned with national objectives.

II. METHODOLOGY

The study adopts a comparative analytical methodology based on a standardized reference floor system representative of commercial and hospitality developments in Saudi Arabia.

A square floor plate with an area of 1000 m² and a regular 9 m × 9 m column grid was selected to ensure comparability across all structural systems while reflecting common regional practice.

A. Structural Systems Definition

5 structural floor systems widely used in the Saudi construction market were investigated, these systems material are presented in Table I:

1) Reinforced concrete flat slab
2) Post-tensioned flat slab
3) Waffle (ribbed) slab system
4) Precast prestressed hollow core slab with structural topping
5) Steel frame with composite metal deck

Preliminary member sizing for each system was established in accordance with typical span-to-depth ratios, serviceability criteria, and constructability considerations commonly applied during concept and schematic design stages. The intent was not to perform detailed structural optimization, but rather to represent realistic early-stage design assumptions consistent with industry practice and the Saudi Building Code.

B. Material Quantification

Material quantities were estimated based on structural layout, slab thickness, and typical reinforcement ratios reported in published literature and regional practice. For reinforced concrete systems, concrete volumes were calculated directly from slab geometry, while reinforcement quantities were derived using representative kg/m³ ratios. For post-tensioned and hollow core systems, both conventional reinforcement and prestressing steel were accounted for. For steel composite systems, steel tonnage was estimated using typical kg/m² values for composite floors with secondary beams.

C. Embodied Carbon Assessment

Although the embodied carbon factors adopted in this study are primarily derived from the ICE Database v3.0, it is recognized that this database reflects a United Kingdom construction context, where electricity grid carbon intensity is relatively low (approximately 0.15–0.20 kg CO_2e/kWh) due to a high share of renewable energy. In contrast, electricity generation in Saudi Arabia remains largely dependent on fossil fuels, with an estimated grid carbon intensity in the range of 0.50–0.70 kg CO_2e/kWh.

The direct application of UK-based factors may therefore underestimate the embodied carbon of energy-intensive materials produced in the Kingdom, particularly cementitious products and structural steel, and may distort the relative environmental performance of alternative structural systems. To address this limitation while maintaining transparency and comparability with existing literature, a two-stage approach is adopted. Baseline results are first presented using standard ICE factors, followed by a Saudi-adjusted asymmetric sensitivity analysis.

TABLE I. EMBODIED CARBON FACTORS ADOPTED FOR THE ASSESSMENT (CRADLE-TO-GATE)

Material	Unit	Embodied Carbon Factor	Source
Ready-mix concrete (C40)	kg CO_2e / m³	300–350	ICE Database v3.0 [12]
Reinforcing steel	kg CO_2e / kg	1.20	ICE Database v3.0 [12]
Prestressing steel	kg CO_2e / kg	1.40	ICE Database v3.0 [12]
Structural steel sections	kg CO_2e / kg	1.70	World Steel Association [13]
Precast concrete elements	kg CO_2e / m³	280–320	WGBC [1]

In the localized sensitivity scenario, the embodied carbon factors associated with cement and steel are increased by +30% to +50%, representing a conservative range consistent with the difference between UK and Saudi electricity grid intensities reported in the literature. Where publicly available information from regional manufacturers (e.g. Saudi Ready-mix and SABIC Hadeed) exists, it has been reviewed qualitatively to confirm the plausibility of the selected adjustment range. This approach allows the robustness of the comparative ranking between systems to be evaluated under Saudi-specific energy conditions without introducing unverifiable assumptions.

The total embodied carbon for each system was calculated by multiplying material quantities by the corresponding carbon factors and summing all contributions. To enable direct comparison, results were normalized and expressed as kg CO_2e/m² of floor area, which is considered best practice for early-stage decision-making.

D. Water–Energy–Carbon Nexus

In hot-arid climates such as Saudi Arabia, water consumption during construction represents an additional and often overlooked contributor to embodied carbon, particularly for cast-in-situ concrete systems.

Conventional flat slabs, waffle slabs, and post-tensioned slabs typically require prolonged on-site curing, while precast systems such as hollow core slabs rely largely on factory-controlled curing processes with limited site water demand.

In Saudi Arabia, construction water is predominantly supplied through desalination, an energy-intensive process with an estimated carbon intensity of approximately 1.79 kg CO_2e/m^3. Neglecting the embodied carbon associated with curing water may therefore bias environmental comparisons in favor of cast-in-situ systems. Due to variability in curing practices, climate exposure, and contractor methodologies, precise quantification of curing water demand is subject to significant uncertainty.

Accordingly, this study incorporates the water–energy–carbon nexus through a qualitative and sensitivity-based assessment, recognizing that the inclusion of desalinated curing water would increase the embodied carbon of cast-in-situ systems relative to precast alternatives. While this effect is not expected to alter the overall ranking of structural systems, its consideration provides a more realistic representation of environmental performance under Saudi Arabian conditions.

E. *Sensitivity Analysis*

A sensitivity analysis was performed to evaluate the robustness of the comparative ranking under two scenarios:

- Variation of embodied carbon factors by ±10%
- Increase in column span from 9 m to 10 m

These scenarios reflect realistic uncertainties encountered during early design development and allow assessment of whether the relative performance of the systems remains consistent.

III. Comparative Assessment of Systems

This section presents a qualitative and semi-quantitative comparison of the investigated structural floor systems prior to detailed embodied carbon quantification. The objective is to establish a clear understanding of how structural efficiency, material demand, constructability, and architectural flexibility inherently influence environmental performance. This comparative assessment provides the contextual basis for interpreting the normalized embodied carbon results presented in the subsequent section.

Reinforced concrete flat slabs are widely adopted in the Saudi construction market due to their simplicity, high architectural flexibility, and ease of service integration. The absence of beams facilitates flexible space planning and reduces coordination challenges with mechanical and electrical services. However, these advantages are typically achieved at the expense of increased slab thickness and reinforcement demand, particularly for medium to long spans, resulting in higher material consumption and an unfavorable embodied carbon tendency.

Post-tensioned slab systems improve structural efficiency by mobilizing prestressing forces to control deflection and cracking, allowing for reduced slab thickness and lower reinforcement quantities compared to conventional flat slabs. This system is commonly adopted in commercial, mixed-use, and hospitality developments where longer spans and reduced floor-to-floor heights are desirable. While post-tensioned construction requires specialized expertise and stringent quality control, it offers significant potential for material optimization at early design stages.

Waffle slab systems utilize a ribbed configuration to reduce self-weight while maintaining stiffness over longer spans. Although material savings relative to flat slabs are achievable, the system introduces increased formwork complexity, longer construction cycles, and higher execution risk. These factors influence constructability and may offset some of the environmental benefits, particularly on projects with tight schedules or limited repetition.

Precast prestressed hollow core slabs are characterized by factory-controlled production, optimized prestressed sections, and rapid on-site installation. The system demonstrates high structural efficiency and reduced concrete volume, contributing to favorable embodied carbon performance. However, architectural flexibility is limited due to predefined slab depths and service zones, making hollow core slabs most suitable for repetitive layouts such as parking structures and residential buildings rather than complex mixed-use configurations.

Steel frame systems with composite decks enable rapid construction and long-span capability, making them attractive for fast-track projects. From a constructability perspective, steel composite floors offer significant schedule advantages. Nevertheless, the steel-intensive nature of these systems generally results in higher embodied carbon when conventional steel production routes are assumed, particularly at early design stages without advanced optimization strategies or low-carbon steel alternatives.

The comparative characteristics of the investigated structural systems are summarized in Table 2, highlighting differences in structural efficiency, constructability, and functional flexibility, while Table 3 qualitatively assesses the key sustainability drivers influencing embodied carbon performance.

TABLE II. Comparative Characteristics of Structural Floor Systems Investigated

Structural System	Structural Efficiency	Constructability	Architectural Flexibility	Typical Application
Flat Slab	Moderate	High	Very High	Commercial, hospitality
Post-Tensioned Slab	High	Moderate	High	Offices, hotels, mixed-use
Waffle Slab	Moderate–High	Low–Moderate	Moderate	Long spans, podiums
Hollow Core Slab	High	High (precast)	Low	Parking, residential
Steel Composite	High	Very High	High	Fast-track projects

TABLE III. QUALITATIVE SUSTAINABILITY DRIVERS INFLUENCING EMBODIED CARBON PERFORMANCE

Structural System	Concrete Volume	Steel Content	Expected Carbon Performance
Flat Slab	High	Moderate	High
Post-Tensioned Slab	Low–Moderate	Moderate	Low
Waffle Slab	Moderate	Moderate	Moderate
Hollow Core Slab	Low	Low–Moderate	Very Low
Steel Composite	Very Low	High	High

Fig. 1 visually reinforces comparative assessment by positioning post-tensioned slabs within a balanced performance zone, while hollow core slabs exhibit the lowest embodied carbon tendency at the expense of flexibility. Flat slabs and steel composite systems, although advantageous in flexibility and construction speed respectively, demonstrate higher embodied carbon tendencies under typical early-stage design assumptions.

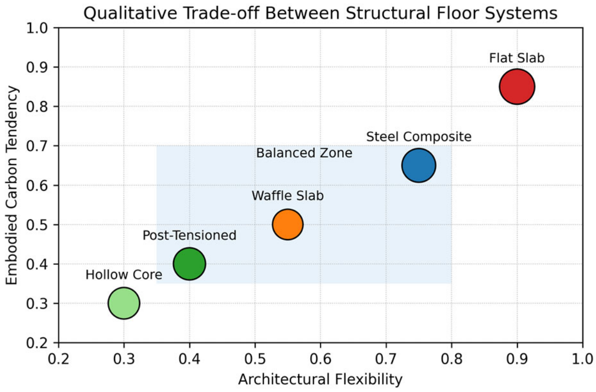

Fig. 1. Qualitative trade-off between embodied carbon, constructability, and architectural flexibility.

IV. RESULTS AND DISCUSSION

The normalized embodied carbon results, expressed in kg CO_2e/m^2, demonstrate clear and consistent performance differences among the investigated structural floor systems, as represented in Table IV and Fig. 2. Normalization per unit floor area enables direct comparison and supports early-stage decision-making where detailed design information is limited.

In addition to embodied carbon, constructability and structural integrity considerations influence the suitability of alternative floor systems in the Saudi context. For post-tensioned systems, long-term performance depends on workmanship quality, grouting effectiveness, and inspection regimes. In coastal cities such as Jeddah and Dammam, exposure to aggressive environmental conditions increases the risk of tendon corrosion if detailing or execution is inadequate, while the requirement for skilled grouting labor may represent a practical constraint within the local construction market.

For precast hollow core slabs, the embodied carbon and cost calculations assume the inclusion of a minimum 75 mm structural topping concrete, which is typically required to achieve diaphragm action, particularly in seismic regions of western Saudi Arabia in accordance with SBC 301. Excluding this topping would underestimate both structural material quantities and associated environmental and cost impacts. These constructability-related factors are therefore considered alongside quantitative results to support balanced system selection.

TABLE IV. NORMALIZED EMBODIED CARBON INTENSITY OF THE INVESTIGATED STRUCTURAL FLOOR SYSTEMS

Structural System	Total Embodied Carbon (t CO_2e)	Floor Area (m²)	Embodied Carbon (kg CO_2e/m^2)
Flat Slab	230	1000	230
Post-Tensioned Slab	115	1000	115
Waffle Slab	160	1000	160
Hollow Core Slab	95	1000	95
Steel Composite System	245	1000	245

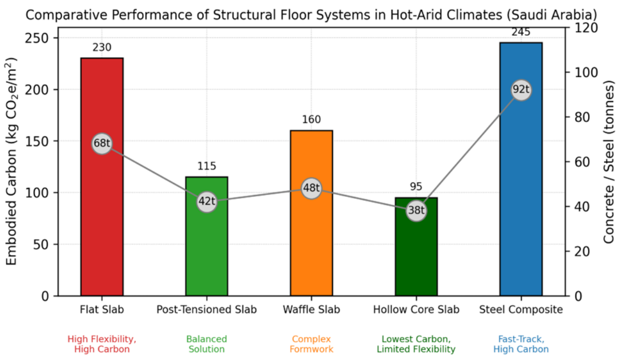

Fig. 2. Normalized embodied carbon intensity of structural floor systems expressed in kg CO_2e/m^2.

Fig. 2 represents, the reinforced concrete flat slab exhibits the highest embodied carbon among the concrete-based systems, reflecting its relatively large concrete volume and reinforcement demand. In contrast, post-tensioned slabs achieve a reduction of approximately 50% relative to flat slabs, primarily due to reduced slab thickness and improved structural efficiency under serviceability requirements.

The precast hollow core system demonstrates the lowest embodied carbon intensity, benefiting from optimized prestressed concrete sections and reduced material usage. However, this environmental advantage is accompanied by reduced architectural flexibility and increased coordination requirements for mechanical and electrical services, which may limit applicability in complex layouts. Waffle slabs provide intermediate performance, offering material savings relative to flat slabs, while introducing increased formwork complexity and longer construction cycles.

The steel composite system records the highest embodied carbon intensity among the evaluated options, despite its advantages in construction speed and long-span capability. The steel quantities adopted in this study represent conservative preliminary estimates based on conventional composite floor configurations, without advanced structural optimization or the use of low-carbon steel alternatives. Accordingly, the results reflect typical early-stage assumptions rather than best-case optimized scenarios.

Sensitivity analysis confirms that the relative ranking of the structural systems remains stable under ±10% variation in embodied carbon factors and modest span increases. Post-tensioned and hollow core systems consistently outperform conventional flat slabs, confirming the robustness of the findings and their suitability for early design guidance.

From a practical perspective, the results highlight critical trade-offs between embodied carbon, constructability, and functional flexibility. Post-tensioned slabs offer the most balanced solution for mixed-use and hospitality developments commonly encountered in Saudi Arabia, while hollow core systems are particularly well suited to repetitive layouts such as parking structures and residential buildings. Steel composite systems remain attractive for fast-track projects but require careful consideration of their environmental impact.

Overall, the findings directly support the objectives of Saudi Vision 2030 and national sustainability initiatives by demonstrating how early-stage structural system selection can deliver significant embodied carbon reductions without compromising project delivery. Integrating embodied carbon considerations into concept design can therefore contribute meaningfully to sustainable urban development while maintaining economic and technical viability.

A. Cost Analysis

To strengthen the practical relevance of the cost comparison and avoid sensitivity to currency fluctuations, a Relative Cost Index (RCI) is introduced. The reinforced concrete flat slab system is adopted as the baseline (RCI = 1.00), and the relative costs of alternative systems are expressed as indices based on typical material quantities, labor requirements, formwork complexity, and specialist construction needs observed in regional practice.

In addition to direct construction costs, the time value of money is an important consideration for large-scale and fast-track developments in Saudi Arabia. Systems such as steel composite and precast solutions, while potentially higher in material cost, can offer significantly shorter construction durations. For giga-projects and revenue-driven developments, accelerated completion may offset higher upfront costs by reducing financing charges and enabling earlier operational income, highlighting the need to evaluate cost alongside construction speed.

Fig. 3 illustrates that cost and embodied carbon rankings do not coincide for structural floor systems in the Saudi market. Post-tensioned slabs exhibit a higher Relative Cost Index due to specialist materials and execution requirements yet achieve significantly lower embodied carbon through improved structural efficiency and reduced concrete volumes. In contrast, steel composite systems are high in both cost and embodied carbon, while flat slabs remain cost-efficient but carbon-intensive. This confirms the importance of multi-criteria decision-making rather than cost-only optimization at early design stages.

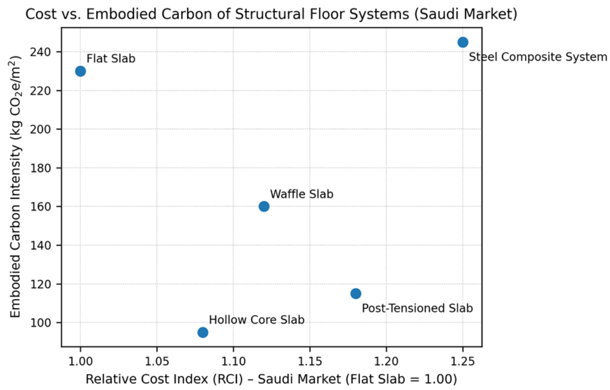

Fig. 3. Cost Vs embodied carbon intensity.

B. Transportation (Module A4)

Saudi Arabia's geographic scale introduces additional uncertainty related to transportation emissions (Module A4) Fig. 4, particularly for precast concrete elements and imported or centrally fabricated steel components. Transport distances between production facilities and construction sites can vary significantly, potentially influencing the embodied carbon of different structural systems relative to on-site cast-in-situ solutions.

To account for this effect, a transportation sensitivity assessment is considered using representative haulage distances (e.g. 50 km versus 500 km). The analysis evaluates whether extended transport distances materially affect the relative ranking of structural systems. While increased transportation emissions may reduce the advantage of precast and steel systems for remote sites, the overall comparative trends remain consistent for typical urban developments, reinforcing the robustness of the study's conclusions.

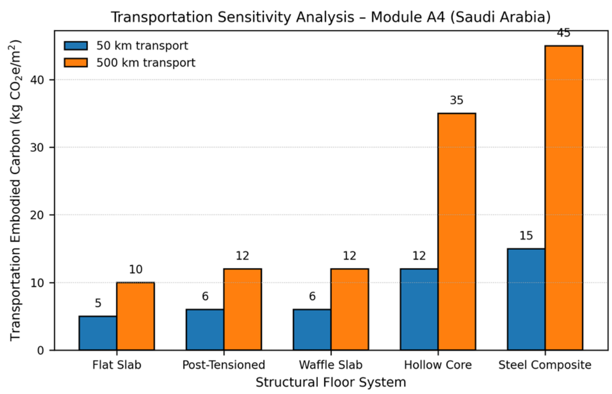

Fig. 4. Transportation Module A4.

Transportation-related embodied carbon is shown for representative haulage distances of 50 km (typical urban supply) and 500 km (remote site conditions). Precast hollow core and steel composite systems exhibit higher sensitivity to transport distance compared to cast-in-situ concrete systems.

V. Conclusion

This study compared commonly adopted structural floor systems in hot-arid regions, with a focus on embodied carbon performance at the early design stage using a consistent assessment framework and normalized indicators. The results demonstrate clear differences between concrete-based and steel composite solutions, showing that post-tensioned and precast hollow core systems achieve significantly lower embodied carbon due to improved structural efficiency and reduced material demand, while conventional flat slabs and steel composite systems exhibit higher carbon intensity under typical preliminary design assumptions. These trends remain consistent under sensitivity analysis, confirming the robustness of the comparative results. Beyond environmental performance, the findings highlight the importance of balancing embodied carbon with constructability and architectural flexibility: post-tensioned slabs offer a balanced solution for mixed-use and hospitality developments, whereas hollow core systems are better suited to repetitive layouts. The analysis is based on preliminary design-level quantities and does not include operational carbon or end-of-life stages; however, it demonstrates that early structural system selection can play a meaningful role in reducing embodied carbon and supporting the objectives of Saudi Vision 2030 and national sustainability initiatives. Future research should extend this work through full life-cycle assessment, integrated cost analysis, and validation using real project data to further strengthen the applicability of the proposed framework.

Conflict of Interest

The author declares no conflict of interest

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